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Fluid Modeling of Pollutant Transport and Diffusion in Stably Stratified Flows over Complex Terrain

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FLUID MODELING OF POLLUTANT TRANSPORT AND DIFFUSION IN STABLY STRATIFIED FLOWS OVER COMPLEX TERRAIN

by

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16. ABSTRACT

A review is provided of stably stratified towing-tank experiments on plume behavior in complex terrain. Recent studies have shown that stratified towing tanks are useful tools to enhance basic physical understanding of transport and diffusion of pollutants over complex terrain as well as to provide practical guidance or "rules of thumb" for locating sources and estimating likely impacts of sources in complex terrain. The concept of a dividing-streamline height, derived from towing-tank studies, provides a useful interpretation of strongly stratified flows. The dividing streamline forms the boundary between a lower layer of essentially horizontal flow and an upper layer that passes over the hill top. Plumes released in the lower layer impact on the hill surface, with resulting surface concentrations essentially equal to those observed at the center of the plume in the absence of the hill. A plume released in the upper layer can be treated as a release from a shorter stack upwind of a lower hill, i.e., as if a ground plane were inserted at the dividing-streamline height. Strongly stratified towing-tank experiments on flows over two-dimensional ridges were found to have no counterpart in the real atmosphere because of the unsteadiness created by the finite length of the tank.

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1. INTRODUCTION

Investigations of pollutant transport and dispersion in the atmosphere over complex relief are critical for the protection of air quality because industrial enterprises and other sources of air pollution frequently locate within complex terrain. The ability to predict ground-level concentrations of air pollutants released from sources in or near complex terrain is required in order to determine the environmental impact of existing sources, evaluate alternative new source locations, designs, and controls, and estimate the effects of possible modifications to existing sources. Mathematical models that reliably predict concentrations when plumes are affected by complex terrain are not yet available. Field studies are very expensive and time consuming, and their results are not generally transferable to other sites.

Wind-tunnel studies on dispersion of effluents from industrial plants located in complex terrain have been conducted for over forty years. Generally, these studies were designed to answer specific questions such as the suitability of a particular plant location or the stack height necessary to avoid downwash; results have not been generally applicable to other sites. In the early wind-tunnel studies, care was taken to ensure a uniform wind profile and low turbulence intensity in the flow aproaching the model. More recent studies have shown that the effects of shear and turbulence intensity (and scales) in the approach flow can strongly affect the basic flow structure over a model (e.g., the turbulence can effect changes in the locations of separation and reattachment points on the lee sides of hills). Therefore, in the past fifteen years serious attempts have been made to simulate the atmospheric boundary layer, including stratification, and to conduct "generic studies" in which idealized terrain features have been used to obtain basic physical understanding. These studies are opposed to "engineering case studies" in which specific questions

are answered with regard to particular installations. Generic studies are most useful when combined with theoretical modeling because theory and experiments tend to direct each other.

This paper attempts to summarize the results of recent stratified towing-tank studies designed to obtain basic understanding of flow and diffusion in complex terrain, provide guidance on locating sources in complex terrain, and provide "rules-of-thumb" for estimating concentrations when a source is located in complex terrain. Many (neutral) wind-tunnel studies have been conducted with the same purpose; these are summarized by Snyder (1984). This current review, however, concentrates on the dramatic and intriguing effects of the stratification.

2. SIMILARITY CRITERIA

Many factors affect the dispersion of pollutants in the atmosphere: thermal effects, topography, rotation of the earth, buoyancy and moisture content of the effluent, etc. Fluid model studies are desirable mostly because essential variables can be controlled, conditions can be reproduced, and the time and expense are greatly reduced from those required in full-scale studies. It is not generally possible, however, for all the factors influencing atmospheric dispersion to be included in a model. Normally, the similarity criteria are conflicting in some sense; it may be necessary to model one physical process at the expense of another. Put another way, certain nondimensional parameters in the prototype must be duplicated in the model for correct modeling. Almost invariably, duplication of all nondimensional parameters is impractical or impossible. Therefore, decisions must be made as to which parameters are dominant; the less important ones must be ignored.

2.1 Basic Parameters

The basic nondimensional parameters for modeling atmospheric processes of different scales are generally agreed upon (Cermak et al 1966, Snyder 1972, Cermak 1976, Snyder 1981) and require only brief mention here.

The Rossby number represents the ratio of advective or local accelerations to Coriolis accelerations. Snyder (1981) concluded from a review of the literature that the Rossby number need be considered when modeling prototype flows with length scales greater that about 5 km under neutral or stable conditions in relatively flat terrain. In modeling flows in complex terrain, we may expect local accelerations to be much more significant than in flat terrain; therefore, prototypes with length scales significantly larger than 5 km may be modeled while ignoring the Rossby number.

Three additional parameters are generally dismissed through use of the concept of Reynolds-number independence. They are (a) the Reynolds number itself, which is a ratio of inertial to viscous forces, (b) the Peclet number, which is the product of the Reynolds number and Prandtl number, and (c) the Reynolds-Schmidt product. These three parameters represent ratios of inertial properties of the flow to molecular properties of the medium. The basic concept of Reynolds-number independence is that if the flow is of sufficiently large Reynolds number, the main structure of the turbulence will be almost totally responsible for the transport of momentum and contaminant (heat or mass). Molecular properties (viscosity and diffusivities) contribute very little to the bulk transfer of momentum, mass, or contaminant; the main consequence of the molecular properties is to smooth out the very small-scale discontinuties of velocity, concentration, or temperature, i.e., the main effect is confined to setting the high wave-number cutoff of the respective spectra. However, molecular properties can be important in the flow very close to a smooth surface (Snyder 1981).

Current practice indicates that sufficiently large Reynolds numbers (sufficiently large to assure Reynolds number independence) are attainable, at least for sharp-edged geometrical structures in ordinary meteorological wind tunnels. However, more work needs to be done to ascertain critical Reynolds numbers for more streamlined surfaces.

The square of the Froude number represents the ratio of inertial forces to buoyancy forces. It is closely related to the Richardson number, commonly used in the meteorological literature to describe the basic stability of the atmospheric boundary layer. However, a different interpretation of the Froude number is quite useful in considering stably stratified flow over hilly terrain. For example, when the flow approaching an isolated hill of height h has a uniform velocity profile and a linear density gradient, the appropriate Froude number is

$$F = [U^2/(gh\Delta\rho/\rho)]^{1/2}, \qquad (1)$$

where $\Delta\rho$ is the density difference between the base and the top of the hill. The square of the Froude number is the ratio of kinetic energy to potential energy, i.e., the ratio of the kinetic energy of a fluid parcel in the approach flow to the change in potential energy of a fluid element as it is raised from the base to the top of the hill. If the Froude number is much less than unity (very strong stratification), there is insufficient kinetic energy in the approach flow to raise fluid parcels from the base to the top of the hill. For a two-dimensional hill perpendicular to the wind, this would result in upstream blocking (Long 1972). For a three-dimensional hill, the fluid, rather than being blocked, can go round the sides. The Froude number is, therefore, most likely the most important individual parameter to be matched when simulating strongly stable flow and diffusion in complex terrain.

2.2 Boundary Conditions

Because of the specification of zero velocity at solid boundaries, geometrical similarity (nondistorted models) is required. However, minute details need not be reproduced. Objects about the size of the surface roughness length need not be reproduced in geometrical form; however, an equivalent aerodynamic roughness must be established. Over-roughening may be required to satisfy a roughness Reynolds number criterion (Snyder 1981).

The approach flow must, in general, simulate the atmospheric boundary layer. Adequate simulations of the neutral atmospheric boundary layer are possible through a variety of techniques. Simulations of diabatic boundary layers have been accomplished using wind tunnels with heated and cooled floors; however, present technology allows only relatively small deviations from neutrality, (mildly stable or mildly unstable conditions). The major problem with wind-tunnel simulation of strongly stable boundary layers is that in order to obtain small Froude numbers (e.g., Fr = 0.2, very strong stability) wind speeds must be reduced to the order of a few centimeters per second. Wind tunnels are generally extremely difficult to operate at low speeds (< 1 m s^{-1}) because they are designed to operate efficiently at their maximum speeds. At these low speeds, the screens and honeycombs designed to reduce turbulence, swirl, and external disturbances are completely ineffective; seemingly minor temperature variations across the test section or leakage through holes or seams in the tunnel sidewalls will easily induce secondary flows that are difficult to cope with. Also, measurement of the flow structure is exceedingly difficult with conventional instrumentation. Finally, because of the very small flow speeds, Reynolds numbers are also quite small, bringing into play the question of the Reynolds number independence of the flow.

A salt-water-stratified towing tank provides an alternative method of

obtaining the required strongly stable conditions without sacrificing the Reynolds number independence condition. Because the kinematic viscosity of water is a factor of 15 smaller than that of air, a factor of 15 in the Reynolds number may be gained by using water as the medium (assuming the same model size and flow speeds).

Other sacrifices must be made, however, in using a towing tank. Because the model is towed through a quiescent medium, the effective approach flow has a uniform velocity profile and zero turbulence intensity. This approach flow does not simulate the nighttime stable atmospheric boundary layer, which is generally very shallow (< 100 m in depth), weakly turbulent, and possesses strong shear (generally a near-linear increase in speed with height). Frequently, however, pollutant sources discharge effluents at much higher elevations, i.e., above the shallow stable boundary layer, where the plume may be transported long distances with little or no dispersion (e.g., see cover photograph, Fourth Symposium on Turbulence, Diffusion and Air Pollution, Am. Meteorol. Soc. 1979). The only dispersion of the effluent (before the plume encounters an obstacle) occurs because of turbulence created at the release point (the stack). Because in very stable conditions the diffusion of chimney plumes is largely determined by initial mixing within the plume (Weil 1983), towing-tank studies can provide reasonable simulations of such conditions.

2.3 Dividing-Streamline Height

In Equation 1, a Froude number was defined that may be used to describe the basic structure of strongly stratified flows over hills. For three-dimensional hills, this structure may be usefully envisioned as composed of two layers: a lower layer of essentially horizontal flow in which plumes from upwind sources impinge directly on the hill surface and an upper layer in which they pass over the hill top. This structure was suggested by theoretical arguments

of Drazin (1961) and demonstrated through towing-tank experiments by Riley et al (1976), Brighton (1978) and Hunt & Snyder (1980). Hunt & Snyder performed salt-water stratified towing-tank studies using a simple bell-shaped hill with a uniform velocity profile and a linear density gradient in the flow aproaching the hill. They showed that under these conditions the depth of the lower layer is predicted as

$$H_D/h = 1 - F, \qquad (2)$$

where H_D is the dividing-streamline height, h is the hill height, and F is the Froude number as defined in Equation 1.

This definition of Froude number, however, is limited in its applicability to uniform wind profiles and linear density gradients. In order to apply the dividing-streamline concept to atmospheric flows, Snyder et al (1984) derived a more general integral formula for predicting the dividing-streamline height for arbitrary shapes of wind profiles and stable density gradients. This integral formula was, in fact, suggested much earlier in a note by Sheppard (1956) based on kinetic/potential energy exchange arguments:

$$1/2\ \rho U^2_{\infty}\ (H_D) = g \int_{H_D}^{h} (h-z)\ (-d\rho/dz)\ dz, \qquad (3)$$

where ρU^2 is to be evaluated far upstream at the elevation H_D and $d\rho/dz$ is the vertical potential density gradient (also far upstream). This formula must be solved iteratively for the unknown H_D. It reduces to the simpler formula (Eq. 2) using the boundary conditions applicable to that case. (It also reduces to another simple fomula derived and verified by Snyder et al (1980) for determining whether an elevated (step) inversion will surmount a hill.)

This dividing-streamline height normalized by the hill height, H_D/h, is suggested here as a more general similarity parameter to be used in place of the Froude number for strongly stratified flows. The utility of this parameter

is immediately evident: plumes released below H_D must impact on the hill surface and/or be transported around the sides with the essentially horizontal flow of the lower layer; plumes released above H_D may pass over the hill top and, in many respects, behave as if they were released at an elevation H_S-H_D upwind of a hill of height $h-H_D$, i.e., as if a ground plane were inserted at the dividing-streamline height H_D.

The parameter H_D/h is useful only if it is positive. (Negative results could be obtained, for example, from Eq. 2 if $F > 1$.) Therefore, this parameter will consitute our definition of "strongly stratified flows" ($0 \leq H_D/h \leq 1$) wherein a lower layer of essentially horizontal flow exists. For weakly stratified flows, we will revert to the Froude number defined in Eq. 1. In that case, $F > 1$ and a lower layer of essentially horizontal flow does not exist.

The strongly stratified flow results to be described in the latter part of this paper will be couched primarily in terms of the dividing-streamline height.

3. TOWING-TANK OPERATIONS

Maxworthy & Browand (1975) described various types of facilities designed to produce stratified flows. The EPA towing tank (1.2 m x 2.4 m x 25 m) uses a two-pump system and a mixing valve to fill the tank with a predesignated shape of stable density profile; it is not limited to the linear density profiles of the two-tank filling method. Typically, a 2.5-cm layer of fresh water is first fed into the tank. A weakly concentrated solution of salt water is then fed into the tank through a distribution piping system on the floor. This heavier solution flows in under and lifts the fresh water. This process continues, each new mixture being slightly heavier than the previous mixture, until the tank is filled. A typical fill consists of a linear density profile of 43 distinct layers; the top layer is fresh water and the bottom layer is saturated

salt water. At the end of the filling operation, the individual layers are visibly distinct; overnight, molecular diffusion tends to smooth the steps in the density profile into a continuous gradient such that individual layers are no longer discernable by eye or by measurement.

The density profiles tend to erode toward neutral at the surface and bottom of the tank because of the towing operations and simple molecular diffusion, although the constant linear gradient is maintained in the central portion. Due to its physical size and the expense, it is not practical to refill the whole tank every few days. Instead, a floating skimmer is used to remove the nonlinear (neutral) layer at the top; the original level is then restored by introducing an additional layer of saturated brine at the bottom. Figure 1 shows density profiles measured about two weeks apart, during which time 36 tows and 5 skims and refills (totalling about 22 cm in depth) were made. The linearity and shape were well maintained, but an increasingly deep layer of nearly constant density fluid accumulated at the bottom. This gradual change in the bottom boundary condition does not appear to significantly affect the study results (Snyder et al 1984).

As a matter of convenience, the hill models are mounted on a flat square baseplate and this apparatus is turned upside down, suspended from the carriage to the point at which the baseplate is submerged a few millimeters below the water surface; the apparatus is then towed the length of the tank. However, in discussion of the flow structure and plume behavior, the results are described as if the model were right side up.

Maxworthy & Browand (1975) provided a good description of instrumentation and techniques used for flow visualization and flow measurements; therefore, only the concentration measurement system will be described here.

The effluent used both for flow visualization and as a quantitative tracer

for concentration measurements is a blue food dye diluted with sufficient salt water to produce a plume that is neutrally buoyant at the release height (typically, 1 part dye to 15 parts salt water). This mixture is emitted from a bent-over "stack", isokinetically to form streamtubes and nonisokinetically to obtain a prescribed plume shape.

During the tow, samples are drawn through ports fixed on the hill surface or on rakes downstream. A vacuum system, shown schematically in Figure 2, is used to withdraw approximately 50 cm^3 of sample through each of the sampling ports into individual test tubes. The concentrations of dye in these samples are analyzed using a colorimeter. Standards of known concentration are analyzed to establish a calibration curve for the colorimeter and a numerical scheme is used to interpolate between calibration points (Snyder & Hunt 1984 supply additional details). This technique permits the measurement of dilutions in the range of 5 to 5000; using a larger concentration of dye in the effluent permits measurements of dilutions to perhaps 50,000.

One problem with the dye is that it leaves a residual in the tank so that the background normally increases with every tow. The dye is controlled by addition of a chlorine bleaching agent. The water is pH-balanced and chlorinated before being placed in the tank. The bleaching process is rather slow; a period of an hour or so is required to bleach out any dye in the tank. A drop of sodium thiosulfate in the sample test tubes neutralizes the chlorine in the sample and prevents bleaching (and hence deterioration) of the samples collected. The dye neutralizes the chlorine during the bleaching process so that the tank may require periodic rechlorination by injecting bleach through a towed rake. In addition, the skimming operation removes contaminated water and the refill operation restores clean and chlorinated water to the surface.

4. THREE-DIMENSIONAL HILLS

4.1 Flow Structure

Plume behavior in complex terrain is dramatically altered by the addition of stable stratification: plume growth is severely inhibited, possibly reduced to zero (Britter et al 1983); if plumes are released below the dividing-streamline height (see Section 2.3), they may be forced to impact on the upwind surface of the hill and travel round the sides (Hunt & Snyder 1980); if released not far above the dividing-streamline height, the plume centerlines may approach very close to the hill surface, resulting in large surface concentrations (Snyder & Hunt, 1984). Under appropriate conditions, the plume may be rolled up into a free-stream rotor above the hill top or possibly into an attached rotor on the lee side of the hill (Castro et al 1983). Vortex shedding in horizontal planes is also possible in the lower layer flow. Examples of each of these phenomena will be presented in the following discussion.

The dividing-streamline or two-layer concept is useful because the transport and diffusion in each layer may be analyzed independently of one another using different but well-established techniques for each layer. For example, because the flow in the lower layer is approximately horizontal, the velocity field outside the wake may be treated as two-dimensional potential flow about a cylinder. The cylinder shape is defined by the contour of the hill at the plume height (Figure 3). Given this mean flow field and the fact that stable stratification limits vertical diffusion, the calculation of dispersion from a point source at height H_S (below H_D) is the same as that from a line source near a cylinder (Hunt, Puttock & Snyder 1979, Weil et al 1981).

In the upper layer, buoyancy and inertial forces control the flow as it passes over the hill. Rowe et al (1982) and Bass et al (1981) have suggested

that this upper layer flow is approximately potential flow. This is not strictly correct, because the stratification above H_D has important effects on the vertical convergence and horizontal divergence of the streamlines (as well as on the diffusion). A better approximation, alluded to in Section 2.3 and demonstrated in Section 4.3, is to treat plumes in the upper layer as if a ground plane were inserted at the dividing-streamline height. By definition, the dividing-streamline height of the upper layer flow is zero (because H_D defines the boundary between the upper and lower layers). Therefore, the Froude number of the upper layer flow is unity and the flow must be treated as if $F = 1$.

Figure 4 illustrates the horizontal flow field in the lower layer. In this case, the hill was a model of Cinder Cone Butte in southwestern Idaho (further discussed in Section 5). The stratification was linear, the dividing-streamline height was $H_D/h = 0.8$, and the dye streamers were released at $H_S/h = 0.3$. Notice that the pattern in the lee of the hill (Figure 4, bottom) looks very much like the familiar Karman vortex street observed downwind of two-dimensional cylinders in neutral flow.

Figure 5 is a view of a free-stream rotor as well as vortex roll-up on the front surface of a hill. In this case, the stratification was linear, the dividing-streamline height was $H_D/h = 0.6$, and the hill was a triangular ridge with base length equal to height and crosswind width equal to four times the height. Castro et al (1983) have studied the lee-wave structure as a function of the stratification and the crosswind aspect ratio. They have shown that the ratio of the crosswind width of the ridge to its height has a negligible effect on the dividing-streamline height.

The conditions for the existence of a vortex on the upwind slope of a hill are not clear. Brighton (1978) calculated vertical deflections of streamlines in stratified flow round a hill; he demonstrated that both vertical shear in the

flow approaching the hill and the hill slope have significant (but opposing) influences. Experiments by Snyder et al (1984) in a stratified shear flow (wind tunnel) tended to confirm the strong and opposing influences of the shear and hill slope; however, more work needs to be done to ascertain the conditions favorable to such vortex formation. Their results, however, suggested that Eq. 3 is a good indicator of dividing-streamline heights, even in strong shear flows, for the vast majority of real hills (i.e., maximum slopes less than 26°).

Snyder et al (1980, 1984) also analyzed an extensive range of laboratory observations and measurements of stably stratified flow over a variety of shapes and orientations of hills with different upwind density and velocity profiles. With a few understandable exceptions (ones that would not generally restrict application to the atmosphere), they reported that the integral formula (Eq. 3) is valid for predicting the dividing-streamline height for a wide range of stable density and velocity profiles and a wide range of three-dimensional hill shapes and orientations.

Some discussion of separation on the lee slopes of hills is in order. Assuming the fluid is infinite in its vertical extent, the fundamental lee-wave mode will have a wavelength of $\lambda = 2\pi U/N$ (N is the Brunt-Vaisala frequency, $[=(g/\rho)d\rho/dz)]^{1/2}$) independent of hill shape. When a hill is of moderate slope and when this wavelength is comparable to the overall length of the hill, large amplitude lee waves are to be expected. The pressure field of the wave acts to suppress separation on the lee face, although it may promote separation downstream, possibly forming a rotor. If the wavelength λ is long compared with the overall length of the hill (weak stratification), we may expect ordinary boundary-layer separation on the lee face, much as in neutral flow separation. If λ is short compared with the hill length (strong stratification), we may expect separation to be lee-wave controlled, i.e., separation will occur at the

first trough of the fundamental lee wave. But all of this depends on the hill slope as well. If the hill slope is small enough, separation will never occur; if it is large enough, separation will always occur near the crest. In very rough terms, for the moderately sloped hills described here, separation on the lee face is controlled by the lee-wave field for $F < 0.8$, it is suppressed for $0.8 < F < 1.2$, and it is boundary-layer controlled for $F > 1.2$. Additional information is provided by Hunt & Snyder (1980), Snyder et al (1980), and Castro et al (1983) (and references contained therein); however, more information is clearly needed to establish the locations and types of separations that occur as functions of hill slope and stratification.

4.2 Plumes in the Lower Layer

The main characteristic of plumes emitted upwind of a hill but below H_D is that they impinge on the hill surface, split, and travel round the sides of the hill (Figure 6). Upwind, the plumes are largely constrained to move in horizontal planes and vertical diffusion is severely limited. They are frequently rolled up within an upwind vortex as they impinge on the hill surface. This behavior does not appear to be regular, steady, or predictable, although the "diameter" of the vortices (i.e., vertical excursions of fluid parcels) appears to be limited to approximately Fh. The vertical plume dimensions increase suddenly and substantially at the upwind stagnation point, whether due to the vortex roll-up or to the vertical divergence of streamlines. These vertical widths are roughly maintained as the plumes are swept round the hill surface. The plumes lose elevation in travelling round the sides of the hill. Plumes that hug the hill surface leave it at the point where the flow separates (generally 100° to 110° from the upstream stagnation point, much as a streamline separates from the surface of a two-dimensional cylinder). Plumes emitted close enough

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to the stagnation line tend to be entrained into the wake region and rather rapidly regain their upstream elevation while mixing through the depth of the jump. Beyond that point, these entrained plumes tend to be vigorously mixed horizontally across the wake, leading to small wake concentrations. Whether or not they are entrained, plumes are generally affected by vortex shedding or low frequency oscillations of the wake. These wake oscillations appear to induce oscillations in the plume upwind of the hill, causing it to waft from one side of the hill to the other.

Snyder & Hunt (1984) showed that, under these conditions ($H_S < H_D$) the maximum surface concentration was essentially equal to the concentration measured at the plume centerline in the absence of the hill (at the same downstream distance). The location of the maximum concentration was on the upstream face. A small lateral displacement of the source from the stagnation streamline did not appreciably change the magnitude of the maximum concentration, but moved its location to the side of the hill. Consequently, small oscillations in wind direction may be expected to result in a covering of the hill with the maximum concentration for short periods, but to significantly reduce the average concentration. Finally, a slightly larger displacement of the source (i.e., a distance comparable to the plume width in the absence of the hill) caused the plume to miss the hill entirely, indicating a very strong sensitivity of surface concentration to wind direction (see further discussion in Section 5).

It is important to understand that, when a plume impinges on a downwind hill, surface concentrations can be essentially equal to those observed at the plume centerline in the absence of the hill. Plume centerline concentrations under stable conditions are typically 3 to 4 orders-of-magnitude greater than for neutral plumes and are even more orders-of-magnitude larger than maximum ground-level concentrations from stable plumes over flat terrain.

A terrain amplification factor for neutral conditions is frequently defined as the ratio of the maximum surface concentration observed in the presence of a hill to the maximum that would be observed from an identical source in flat terrain. Use of this terrain amplification factor in stable conditions would result in extremely large numbers that would be difficult to interpret. Therefore, a different terrain amplification factor is defined for stable flows as the ratio of the maximum observed surface concentration in the presence of a hill to that observed at the plume centerline at the same downwind distance in the absence of the hill.

4.3 Plumes in the Upper Layer

Plumes emitted above H_D, of course, are transported over the hill top; however, if the release height is close to the dividing-streamline height, they spread broadly but thinly to cover the entire hill surface above H_D (Figure 7). Unlike plumes released at or below H_D, plume material reaches the hill surface only by diffusion perpendicular to the plume centerline. Plume meander as observed at or below H_D is absent. As H_S is increased relative to H_D, the point of first contact of the plume with the hill surface moves toward the hill top; further increases in H_S move the contact point to the lee side of the hill (Figure 8). These features, in combination with the steadiness in the flow and thus the plume direction, have resulted in some of the largest surface concentrations observed under any conditions. With still further increases in H_S, the plume moves off the hill surface and surface concentrations diminish rapidly.

As discussed in Section 4.1, some mathematical models treat the upper layer as potential flow; this is not strictly correct because potential flow does not allow for the effects of the stratification. Also, as discussed in Section 4.1, the upper layer flow may be treated as flow over a smaller hill with a Froude number of one ($H_D = 0$). We will examine these two approximations in some detail.

Figure 9 shows a comparison of hill centerline concentrations from sources of three different heights measured, in one case, in the neutral and uniform approach flow of a wind tunnel and, in another case, in the strongly stratified ($F = 1$ or $H_D = 0$) towing tank (Snyder & Hunt 1984). These concentrations have been normalized by the maximum concentrations found at the centers of the plumes in the absence of the hill (to compensate for the differing diffusivities in the wind tunnel and towing tank).

Pursuant to the discussion at the end of Section 4.1, we may expect boundary-layer separation on the lee side of the hill in the neutral wind-tunnel flow, but total suppression of separation due to the stratification in the towing tank. The point of flow separation on the lee side of the hill under neutral conditions is clearly evident in Figure 9; a sharp decrease in concentration was observed at $x/h \approx 0.5$ ($z/h \approx 0.9$) for stack heights of 0.13h and 0.39h. In contrast, at $F = 1$ the flow swept the plumes continuously down the lee side of the hill (no separation) so that changes in concentration along the hill surface were relatively smooth. Because of the separation, lee side concentrations between the neutral and stratified cases differed by up to factors of ten. Upwind of the separation point, the effect of the stratification appeared to be small, with concentrations differing by much less than a factor of two. A tentative conclusion here is that for rough estimates, potential flow may be a fair approximation for the upper layer flow in strongly stratified conditions <u>if</u> the maximum surface concentration is found to occur well upwind of the separation point in neutral flow or if separation does not occur in neutral flow. Implicit here is that appropriate diffusivities are used in calculating the plume spread.

It is interesting to note that the maximum surface concentration decreased by a factor of three when the source height was increased by a factor of three (from 0.13h to 0.39h). Theoretical arguments suggest that over level ground

this decrease would have been H_2^2/H_1^2, or a factor of nine.

We have previously alluded to the idea that the upper layer flow may be treated as flow over a smaller hill with a Froude number of unity, i.e., as if a ground plane were inserted at the dividing-streamline surface. It is known from laboratory studies that even well within the lower layer streamline trajectories are not contained within horizontal planes. On the other hand, concentration measurements suggest that a flat surface approximation may yield reasonable estimates. From a practical viewpoint, mathematical models are vastly simplified if such an assumption yields reasonable estimates of surface concentration. Snyder & Lawson (1984) conducted a series of towing-tank studies to examine surface concentration patterns resulting from upwind plumes released in the upper layer and, more specifically, to test the adequacy of the assumption of a flat dividing-streamline surface. They attempted to answer the question, not from a detailed analysis of the shape of such a surface, but from the more practical comparison of surface concentration patterns.

In the Snyder and Lawson experiments, linear density gradients were established in the tank and the hill was towed at a speed U such that the Froude number F was 0.5 ($H_D/h = 0.5$). Effluent was released at a height of 0.6h and the resulting hill-surface concentration patterns were measured. A second tow was conducted in which the entire model (hill, baseplate and stack, as a unit) was raised out of the water to the point where the water surface was precisely at the dividing-streamline height, i.e., the water surface was at half the hill height. The model was towed at the same speed as in the full-immersion tows so that the Froude number of this now half-height hill was unity and all streamlines passed over the hill top. The flat water surface thus forced a flat dividing-streamline surface. The resulting surface concentration patterns were then

compared with the full-immersion patterns to ascertain the effects of a flat dividing-streamline surface.

Figure 10 shows a comparison of the concentration distributions resulting from the full- and half-immersion tows. The plumes were spread broadly to cover essentially the entire surface above half the hill height (the dotted circle on the figure marks half the hill height). The contours on the windward side of the hill are roughly circular, although somewhat elongated in the streamwise direction. In the half-immersion case, no concentrations were observed below half the hill height, of course, because that portion of the model was out of the water. In the full-immersion case, the plume "hugged" the lee side of the hill and was swept to elevations considerably lower than half the hill height.

Figure 11 is a scatter diagram comparing, on a point-by-point basis, the surface concentrations measured in the half- and fully-immersed cases. Within the region of large concentrations, the two cases compared quite favorably; the half-immersed case yielded concentrations approximately 10 to 20% larger than the fully-immersed case. In the region of low concentration, quite large differences occurred (worst case: a factor of ten). However, a close examination shows that in all cases in which the concentrations differed by more than a factor of two, the sampler locations were very close to half the hill height, i.e., either at 0.505h or 0.51h.

These results suggest that the assumption of a flat dividing-streamline surface in a mathematical model is a reasonable approximation to make, at least with regard to predicting the locations and values of maximum concentrations and areas of coverage.

4.4 Further Discussion

Figure 12 presents an overview of the maximum surface concentrations measured in H_s/h x F space for the bell-shaped hill of Snyder & Hunt (1984).

Overlaid on this graph are the dividing-streamline height ($H_D/h = 1 - F$), the boundary layer, and somewhat speculative isoconcentration lines. These isoconcentration lines were drawn to fit the data as measured, but a generous allowance was made for scatter in order that they might also satisfy our physical intuition. The graph suggests that the largest concentrations occur when the source release is near the dividing-streamline (the solid line in the graph) and that they decrease rapidly with distance to the right of this line (larger stack heights or Froude numbers). This rapid decrease is due to the fact that as the stack height or Froude number is increased, the contact point moves upward over the hill top and then down the lee side; further increases in $H_S - H_D$, much above the thickness of the plume in the absence of the hill Σ_z^o, result in the plume lifting off the surface with no contact at all. Note that if $H_S - H_D \approx \Sigma_z^o$, a significant surface concentration can arise because of the downward deflection of the streamlines onto the hill. If the source height is less than the dividing-streamline height (left of the line), the measurements suggest that the maximum surface concentrations are roughly uniform in this region. However, visual observations during the tows suggested that the lower the stack height the more prominent was the plume meander (hence, lower concentrations), although the actual surface concentration seemed to depend on the precise point at which the plume entered the vortex on the upwind slope. The size and elevation of these vortices appeared to vary from one tow to the next (indeed, even during a single tow) and were not investigated in detail.

For the very small stack heights, the plumes dispersed relatively quickly in the surface boundary layer over the baseplate so that concentrations were essentially independent of the hill Froude number. Recall that the hill Froude number is a bulk parameter that characterizes the overall flow over the hill; the Froude number characterizing the boundary layer flow is much larger because

of the smaller scale of the boundary layer ($\delta << h$) and the reduced density gradient caused by the mixing.

5. COMPARISONS WITH FIELD EXPERIMENTS

While much has been learned about flow and dispersion under stable conditions, the applicability of towing-tank results to the atmosphere is sometimes questioned. The height of the dividing-streamline is directly proportional to wind speed; in a towing tank, the wind speed is constant. The unsteadiness of the wind in the field, however, can allow the plume to impact on the front surface at one moment, then sweep it over the top at the next moment. Similarly, a meandering wind will result in a plume being swept from one side of the hill to the other, resulting in significant reductions of surface concentration. Carefully designed field studies are required to determine the effects of these aspects of atmospheric flows and to aid in the interpretation of towing-tank results so that full-scale predictions can be made.

In a major field study recently completed, Lavery et al (1982) collected six weeks of data on flow and dispersion around a 100-m high, isolated hill (Cinder Cone Butte) in a broad, flat river basin in southwestern Idaho. Detailed measurements were made of wind, turbulence, and temperature profiles in the approach flow and at other positions on the hill. SF_6 as a tracer and smoke for flow visualization were released from a mobile crane that allowed flexibility in positioning the source (height and location). One-hundred samplers on the hill collected data on surface concentrations. LIDAR was used to obtain plume trajectories and dimensions. The study concentrated on stable plume impaction.

One particular hour from that field-study data was selected for simulation in the towing tank (Snyder & Lawson 1981). That hour was 0500 to 0600, October 24, 1980 (Case 206), which may be characterized as very stable, i.e., light

winds and strong stable temperature gradients. Measurements made during the towing-tank experiments included ground-level concentrations under various stabilities and wind directions, vertical distributions of concentration at selected points, plume distributions in the absence of the hill, and visual observations of plume characteristics and trajectories.

This series of tows showed that the surface concentration distributions were extremely sensitive to changes in wind direction. For example, Figure 13 shows that the distribution shifted from the north side of the hill to the south side with a shift of only 5° in wind direction. Comparisons of individual distributions with field results showed very much larger maximum surface concentrations and much narrower distributions in the model results. To account for this variability in the winds measured during the hour, a matrix of 18 tows (three wind directions x six wind speeds) was conducted and the concentration patterns were superimposed. A scatter plot of superimposed model concentrations versus field concentrations (Figure 14) showed a marked improvement over the previous single-tow comparisons. The largest model concentrations were within a factor of two of the highest field values.

It is interesting to note that, whereas the location of the maximum shifted dramatically with small shifts in wind direction, the value of the maximum changed very little with changes in wind direction or wind speed. Maximum surface concentrations approached those at the plume centerline in the absence of the hill during individual tows but, because of the extreme sensitivity of the location to wind direction, the plume was "smeared" broadly across the hill surface as the wind direction changed through only a few degrees. Therefore, short-term averages (≈5 min) in the field may be expected to approach plume centerline concentrations; longer term averages (≈1 h) may be expected to be reduced by factors of from five to ten (or more, depending on the magnitudes of

fluctuations in wind speed and direction).

6. TWO-DIMENSIONAL HILLS: LIMITATIONS OF TOWING TANK

In our previous discussions of the dividing-streamline concept, we implicitly assumed that the portion of the flow with insufficient kinetic energy to surmount the hill top was able to pass around the sides of the hill. However, if the model is two-dimensional (spans the width of the tank), the fluid with insufficient kinetic energy is blocked or trapped upstream. Because of continuity, the blocked fluid must conserve its volume. Therefore, as the distance between the model and the upstream endwall of the tank decreases, the blocked fluid is "squashed", i.e., because the length of the blocked region must decrease with distance along the tow, the depth of the fluid that was initially blocked must increase. Eventually, all of the fluid upstream of the model will spill over the top. The fixed end on the tank, in effect, provides a uniform approach flow velocity profile at a distance upstream of the model that varies as the experiment progresses.

Snyder et al (1984) addressed this problem through a series of towing-tank studies. They used a series of "infinite" ridges of quite different cross-sectional shape to test the validity of the "steady-state" assumption of flow upwind of two-dimensional ridges under strongly stratified conditions. Three ridge shapes were used: a vertical fence, a triangular ridge with a slope of 63°, and a Witch of Agnesi $[1/(1 + x^2)]$ with a maximum slope of 39°.

Results will be shown here only for the triangular ridge. A density sampling rake was positioned 11-hill-heights upwind of the ridge and towed with the ridge. Density samples were collected just prior to the start of the tow, during the first and last meter of the tow, and at the one-third and two-thirds points of the tow (the total length of the tow was approximately 20 m). The experiments were conducted at a Froude number of 0.5 (based on the tow speed and the

undisturbed density profile) so that the calculated depth of blocked fluid (the dividing-streamline height) was 0.5h.

Figure 15 shows the density profiles collected during these tows. The initial near-linear density profile was continuously modified during the tow at a position 11-h upstream and that upstream conditions did not reach steady state. The profiles tended toward neutral at elevations below half the hill height.

The conclusion from this series of studies was that steady-state conditions are not established in strongly stratified flows (i.e., $F < 1$) over two-dimensional ridges in finite-length towing tanks. The "approach flow" velocity and density profiles changed continuously during the tow. Thus, these experiments have no analog in the real atmosphere.

7. CONCLUSIONS

The effects of stratification on plume behavior in complex terrain are dramatic and fascinating. Depending on the release height and the Froude number, plumes may be observed to impact on hills, to sweep narrowly over the tops of hills, or to be entrained into rotors or vortices of numerous types. The stratification may either enhance or inhibit separation on the lee sides of hills. A stratified towing tank is a useful tool to enhance basic physical understanding of such phenomena and provide practical guidance or rules of thumb for locating sources and estimating likely impacts of such sources in complex terrain.

The Froude number is quite likely the most important single parameter to be matched when simulating strongly stable flow and diffusion in complex terrain. A closely related but more general parameter, the dividing-streamline height, provides for a more useful interpretation of strongly stratified flows. The dividing-streamline forms the boundary between a lower layer of essentially

horizontal flow and an upper layer that passes over the hill top.

Plumes released in the lower layer impact on the hill surface; the resulting surface concentrations essentially equal those observed at the center of the plume in the absence of the hill.

For practical purposes, a plume released in the upper layer can be treated as a release from a shorter stack upwind of a shorter hill, i.e., as if a ground plane were inserted at the dividing-streamline height.

A comparison of field and laboratory observations of concentration patterns on a hill surface under strongly stratified conditions showed very good correspondence when wind speed and direction variability were accounted for in the model experiments. Concentration distributions on the hill surface were found to be extremely sensitive to slight changes in wind direction.

Finally, strongly stratified towing-tank experiments on flows over two-dimensional ridges were found to have no analog in the real atmosphere because of the unsteadiness created by the finite length of the tank.

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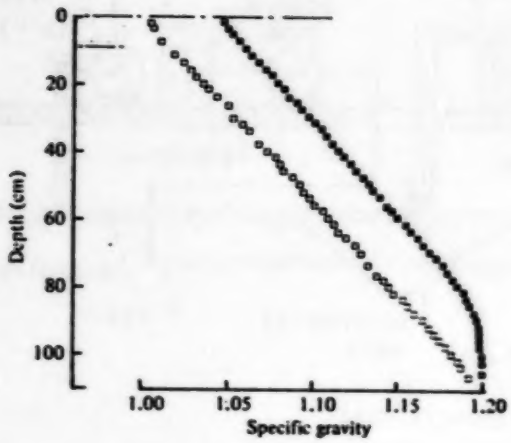

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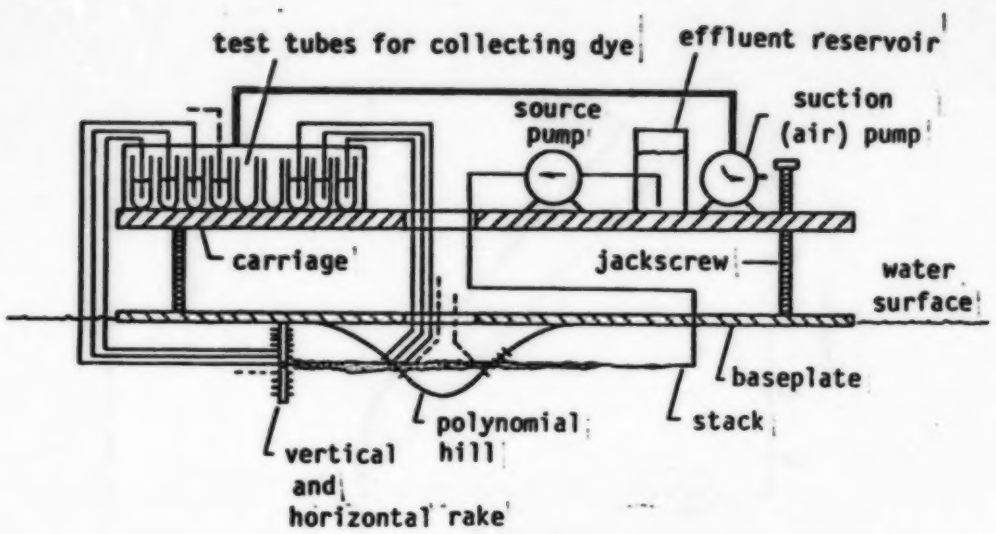

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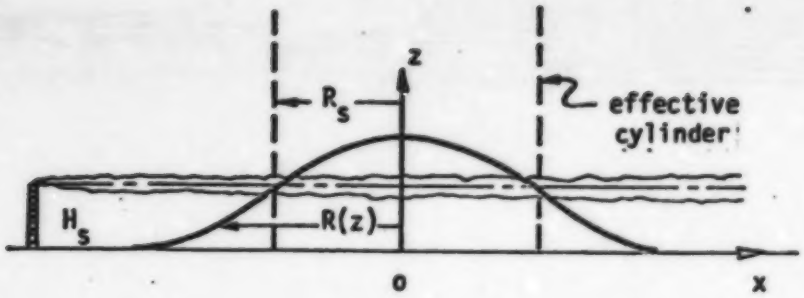
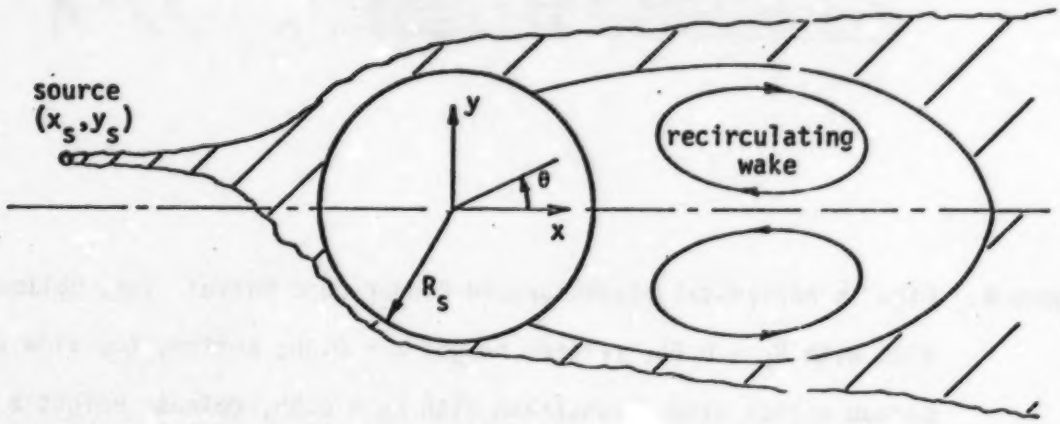


(a) Side view of plume impinging on hill at low Froude number.



(b) Section through hill, plume and wake at $z = H_s$.

Figure 3. Simplification of plume impingement on three-dimensional hill under very stable stratification.

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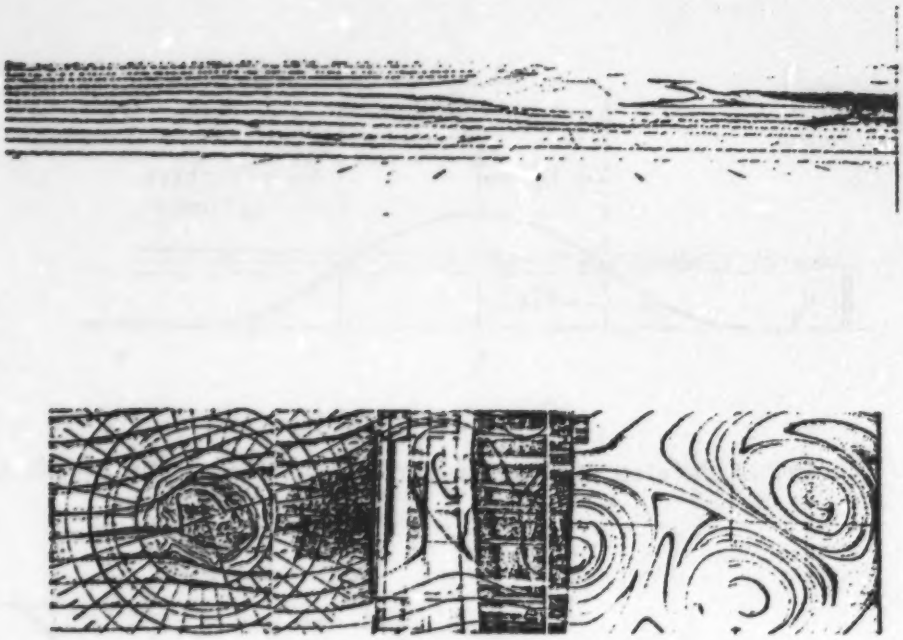

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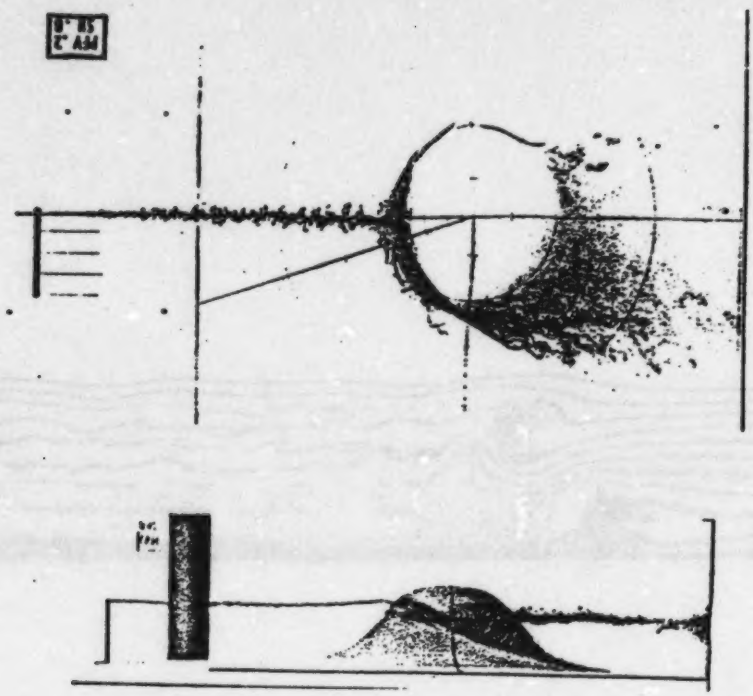

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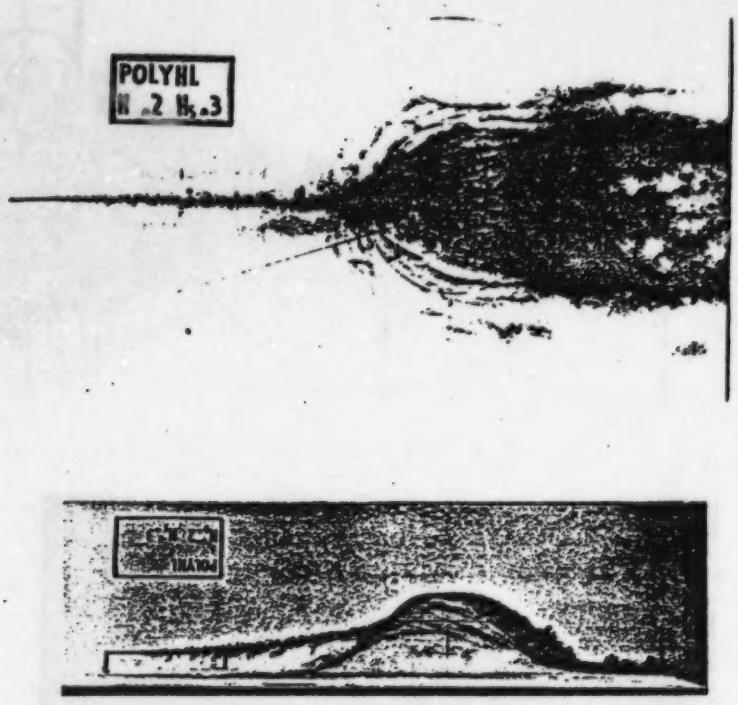

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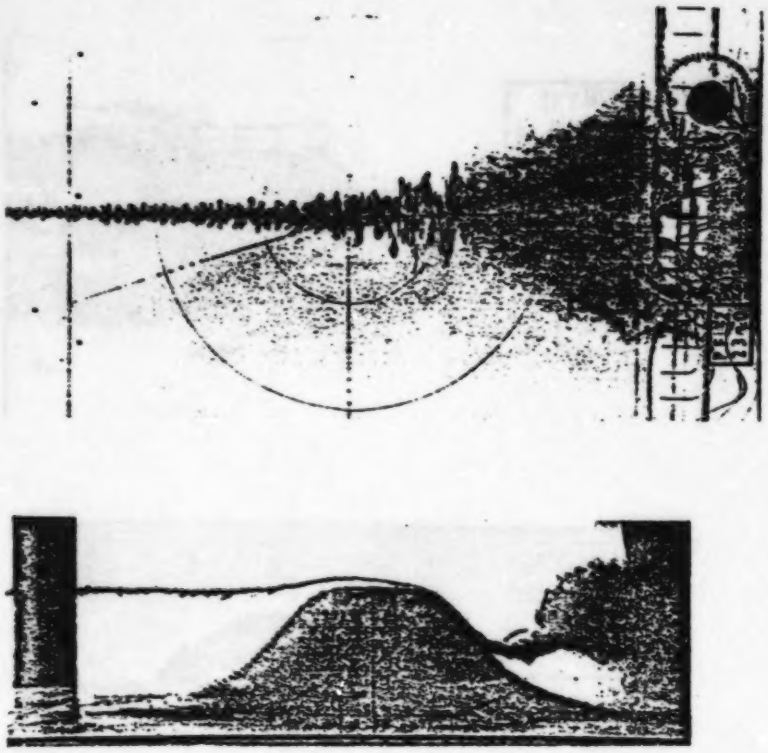
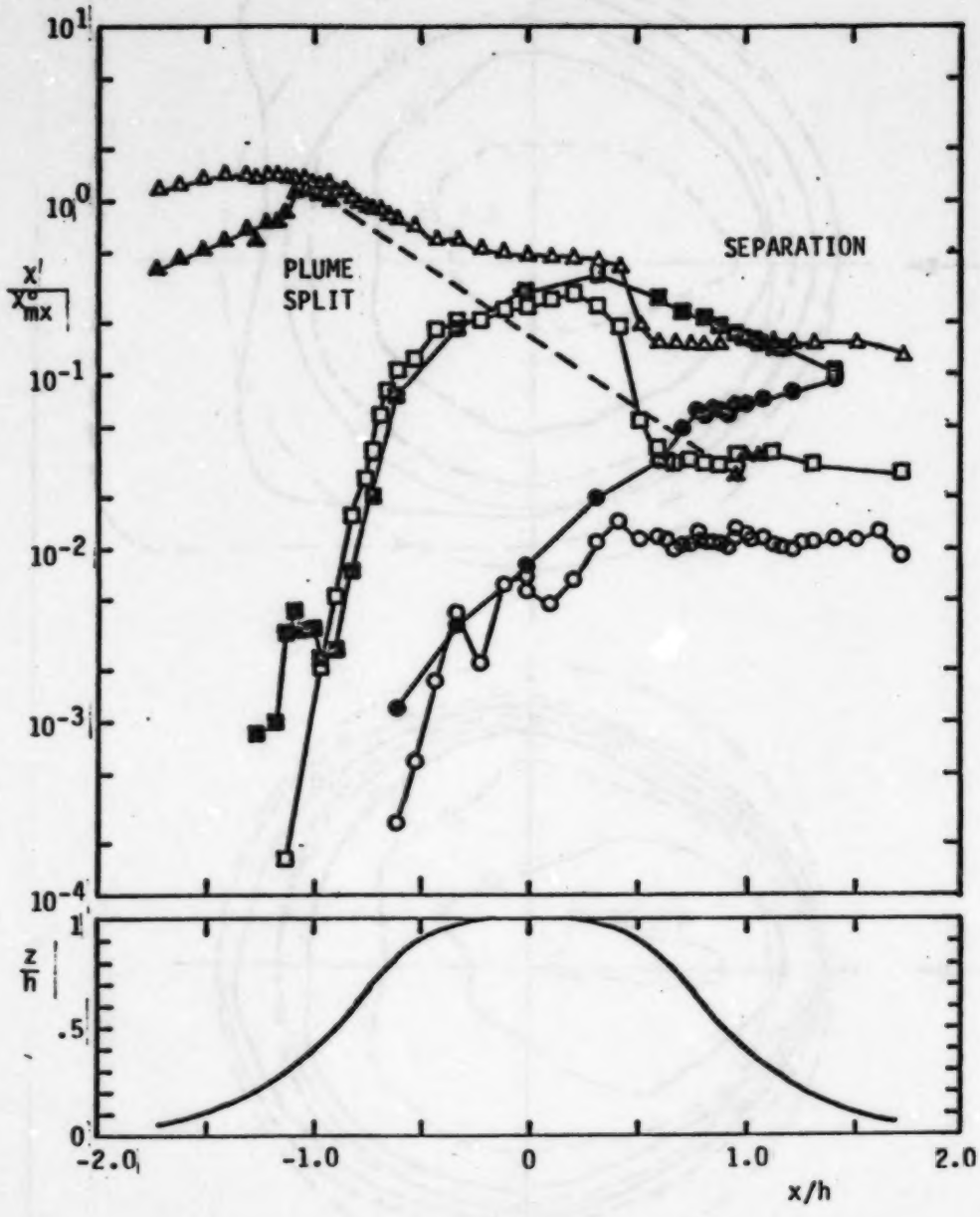


Figure 8. Lee side contact of plume with hill: $H_D/h = 0.6$, $H_S/h = 1.0$.



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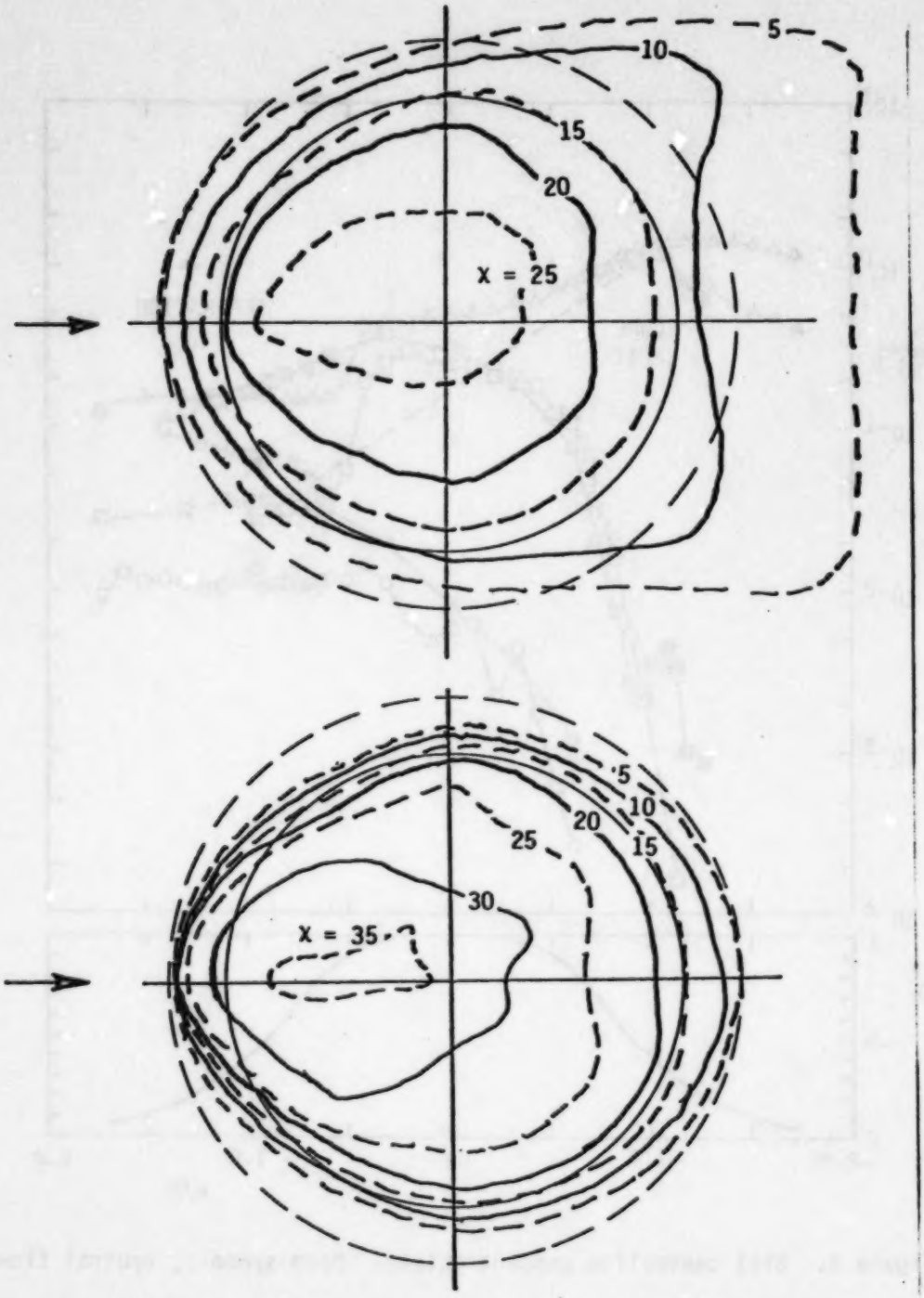

Figure 10. Concentration distributions measured on the hill surface. $H_D/h = 0.5$, $H_S/h = 0.6$. Top: fully submerged; Bottom: half submerged.

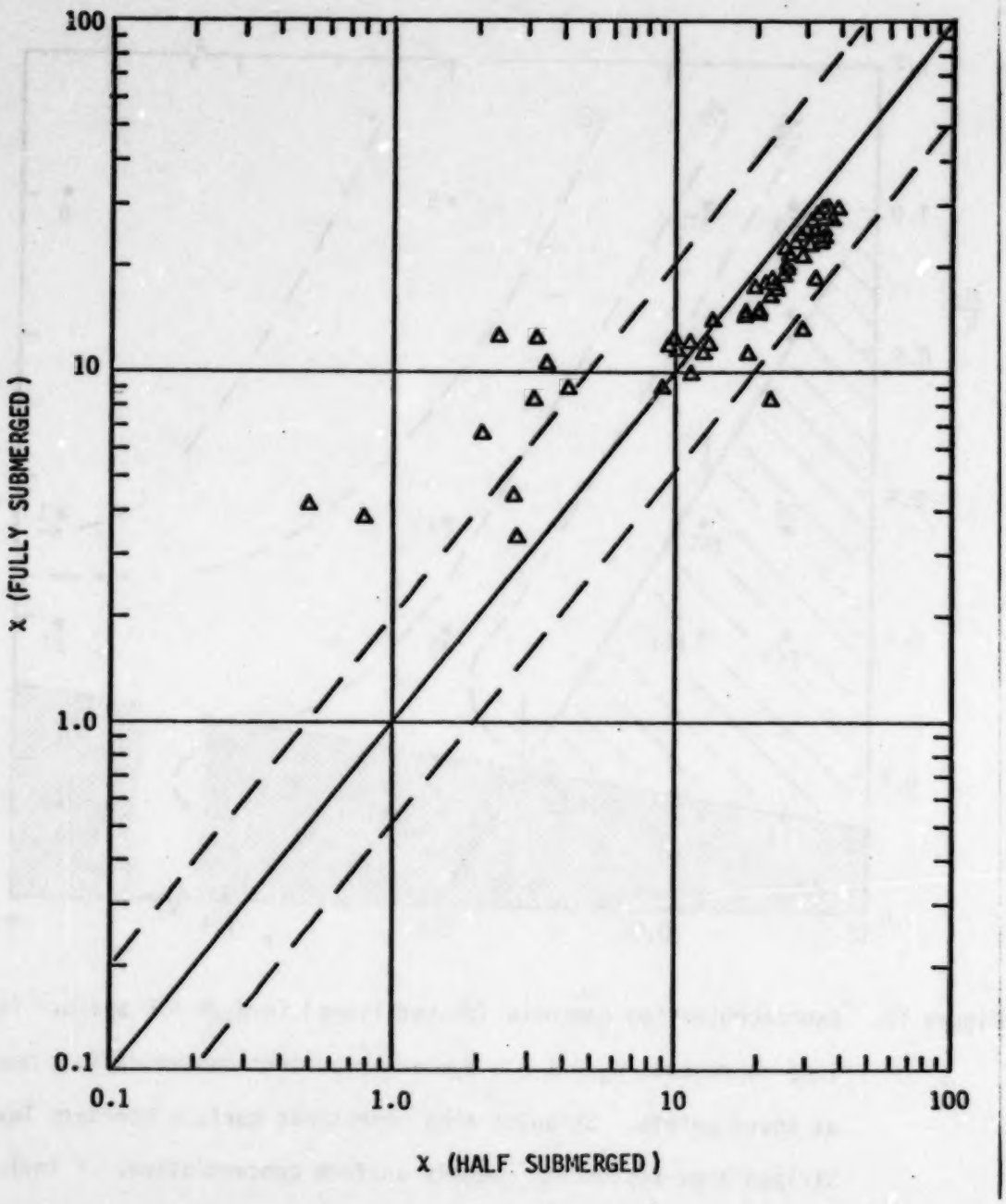

Figure 11. Comparison of concentrations. Half submerged versus fully submerged. $H_D/h = 0.5$, $H_s/h = 0.6$.

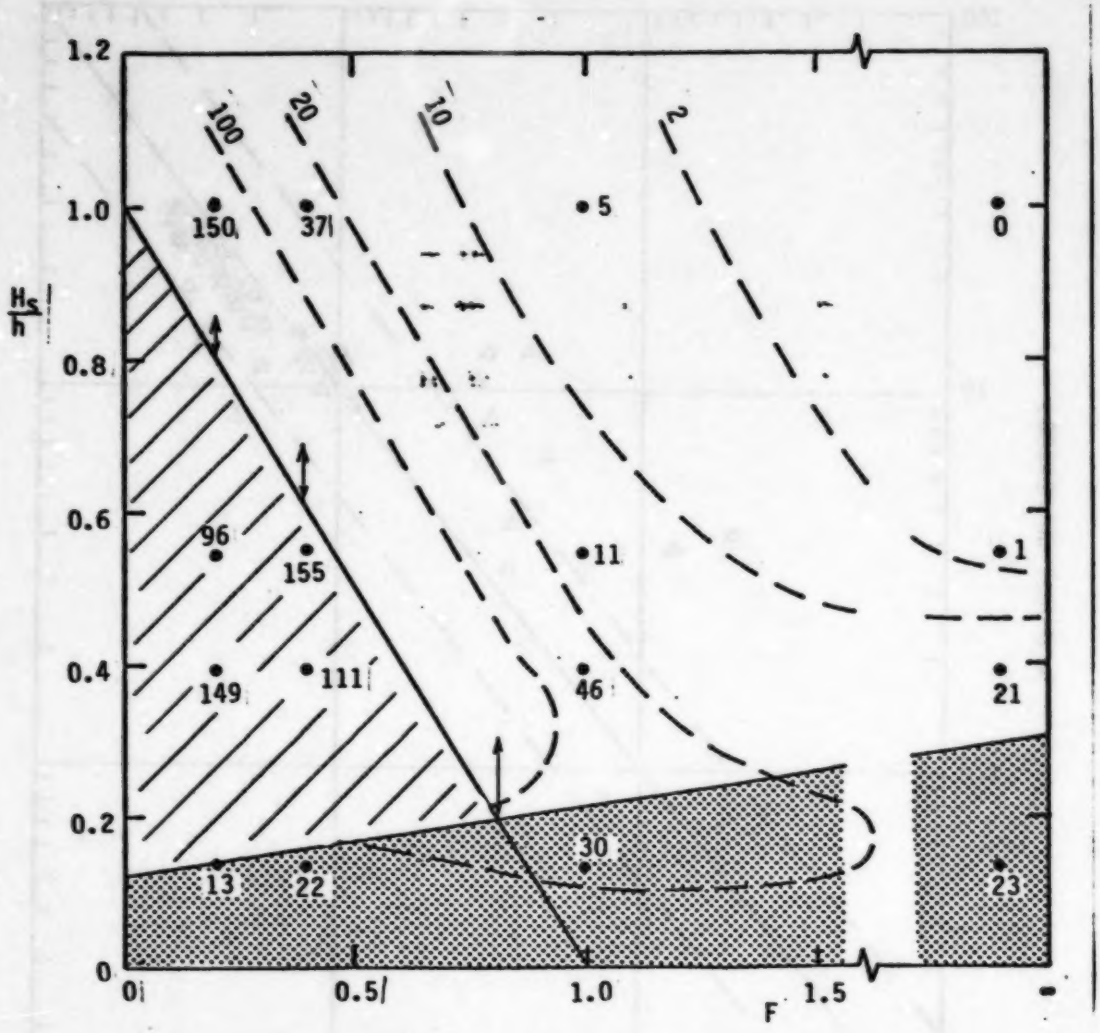

Figure 12. Isoconcentration contours (dashed lines) in $H_s/h \times F$ space. Solid line represents $H_s/h=1-F$. Numbers represent concentrations measured at those points. Stippled area represents surface boundary layer. Striped area represents roughly uniform concentration. † indicates Σ_z^o/h, the depth of the plume at the location of the hill.

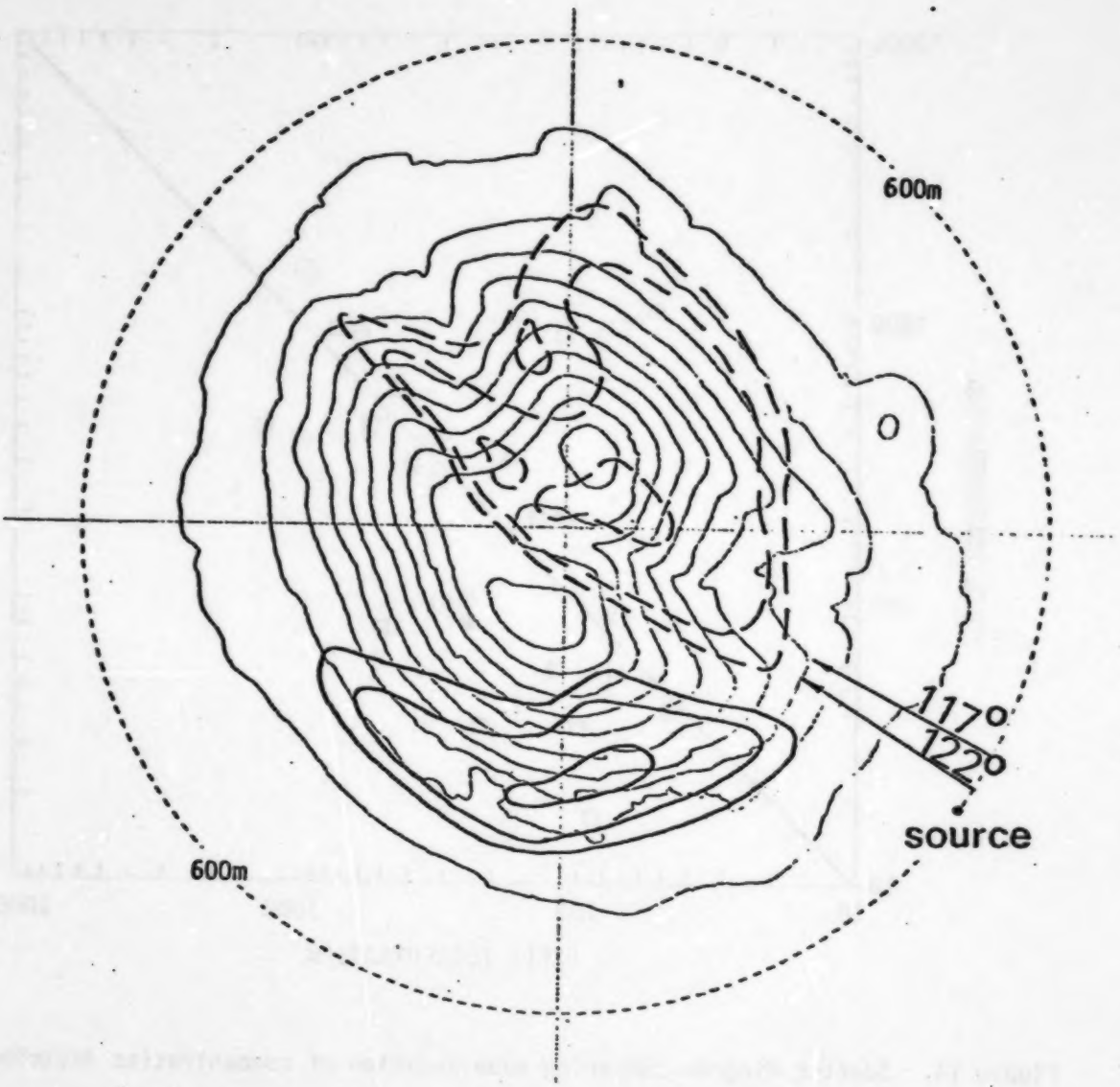

Figure 13. Concentration distributions measured during individual tows: $H_S/h = 0.31$, $H_D/h = 0.38$; wind direction: —— 117°, ---122°.

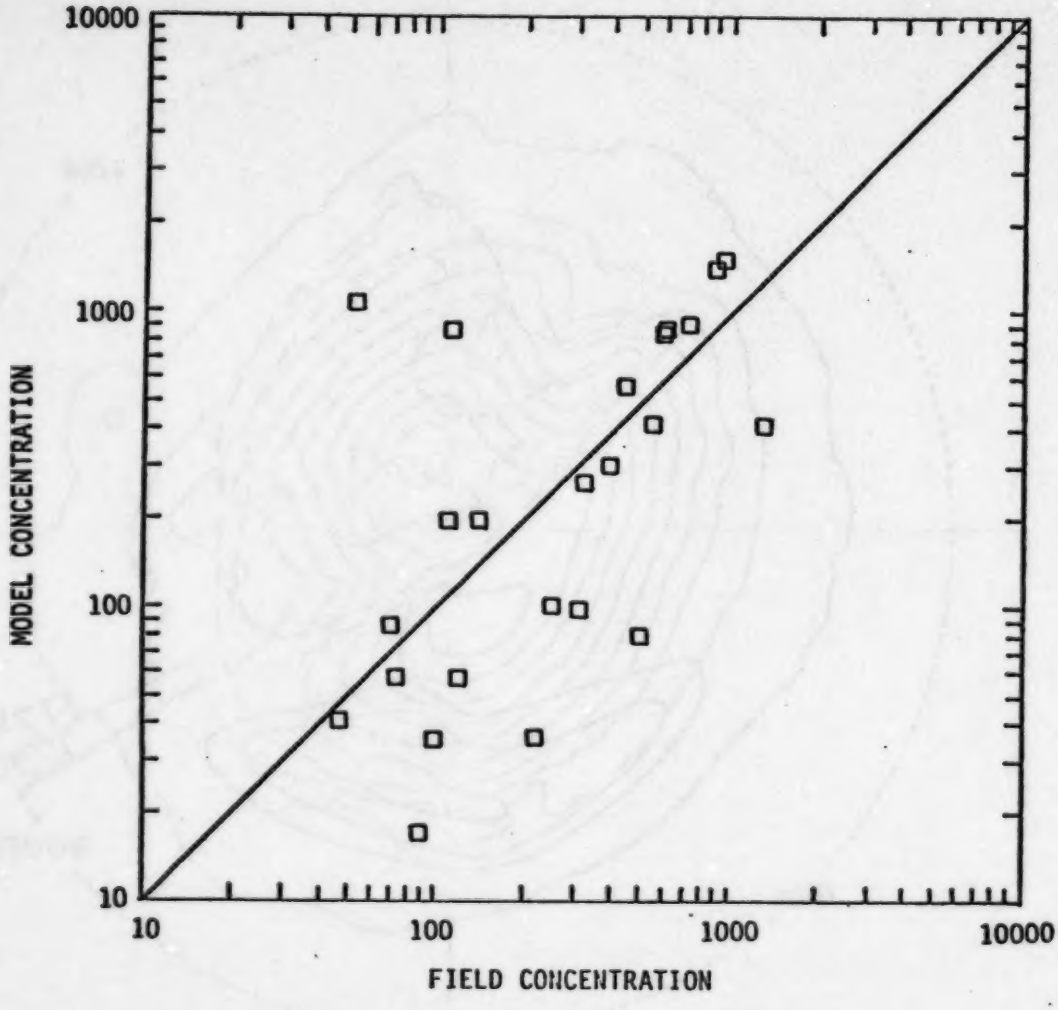

Figure 14. Scatter diagram comparing superposition of concentration distributions measured over Cinder Cone Butte.

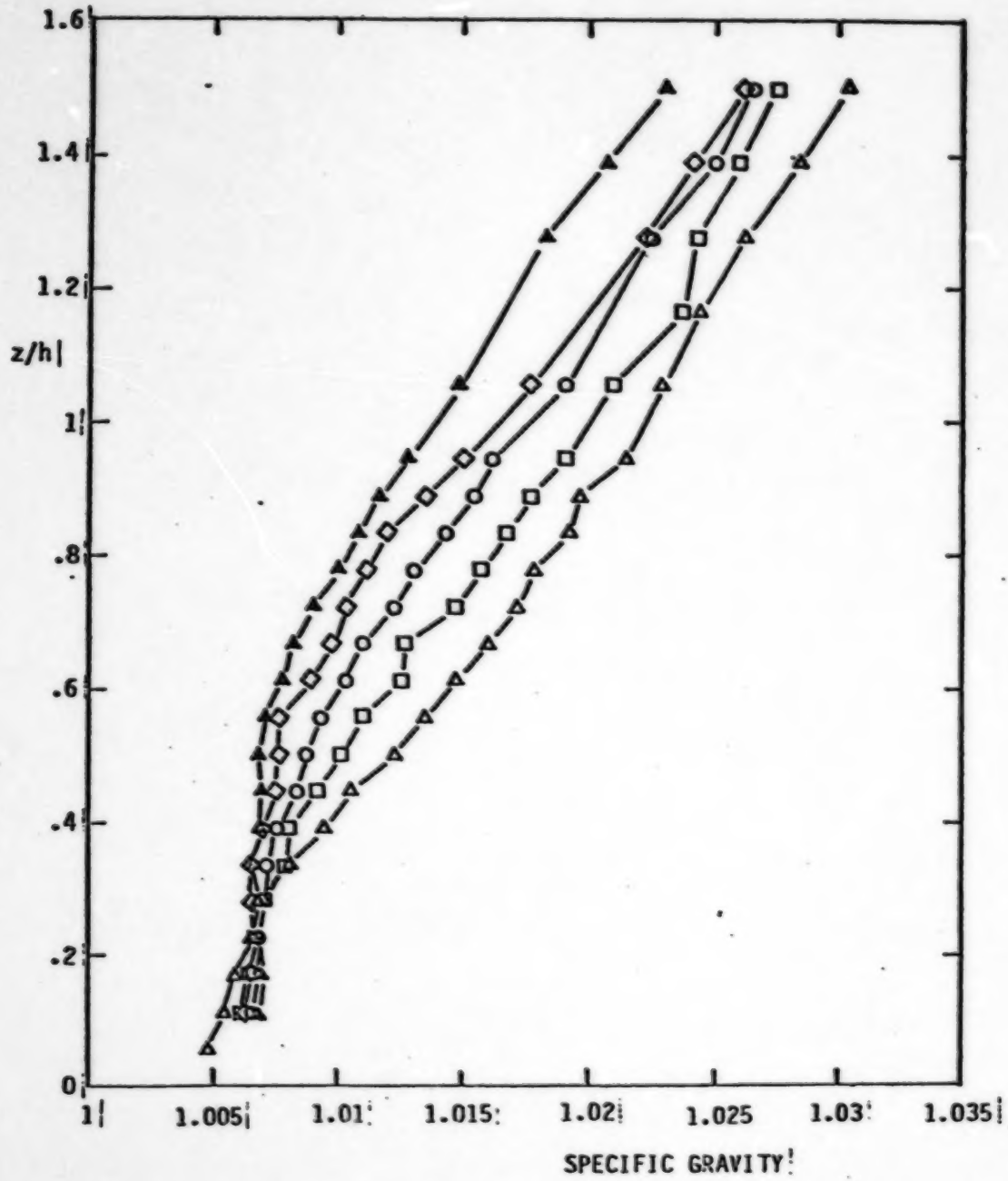

Figure 15. Density profiles measured 11 hill heights upstream of two-dimensional triangular ridge. △, initial density profile. Sampling interval centered at x=: □, 1.3 m; ○, 6.7 m; ◇, 11.8 m; and ▲, 17.7 m from start of tow.